Scaled III-V optoelectronic devices on silicon

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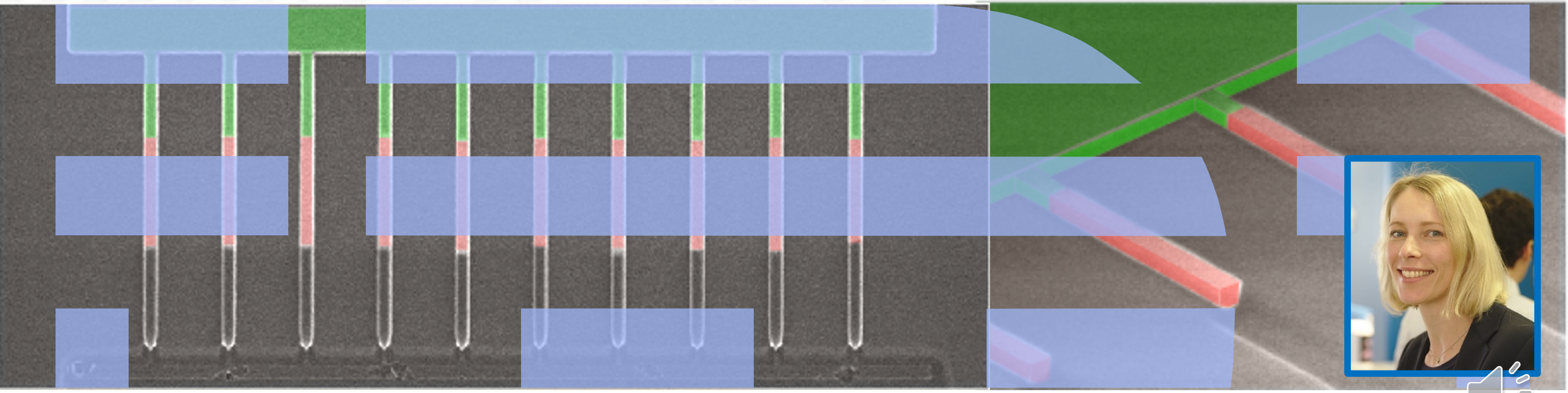


Materials Integration and Nanoscale Devices Group

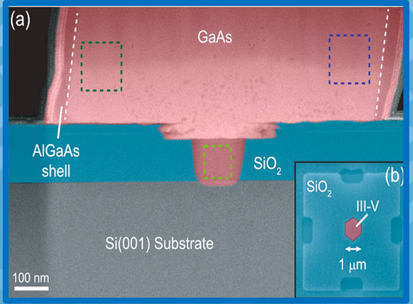
Numerical Simulation of Optoelectronic Devices

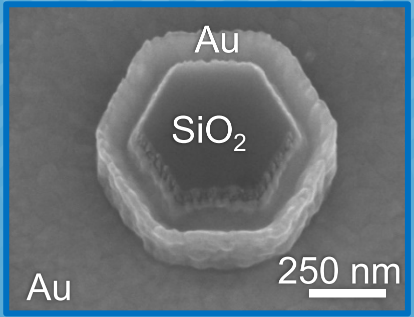
Objective of this talk:
Connecting Theory and Application of Optoelectronic Devices

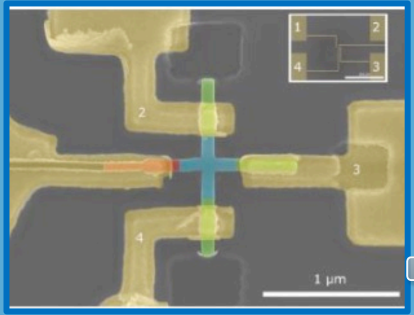
- Discuss some of the challenges related to III-V on Si integration
- Give you an overview of some of the devices we are working on – emitters and detectors.
- Show how simulations may be essential for device understanding
- Provide guidelines to which problems may be addressed by simulation

Overview

- **Motivation and intro – III-V on Si**
- **Template-Assisted Selective Epitaxy (TASE)**
- **III-V TASE microdisk lasers**
- **Two examples – interaction with simulation**
  - *Monolithic InGaAs detectors*
  - *Nanolaser scaling with metal-clad cavities*
- **Summary & Conclusion**





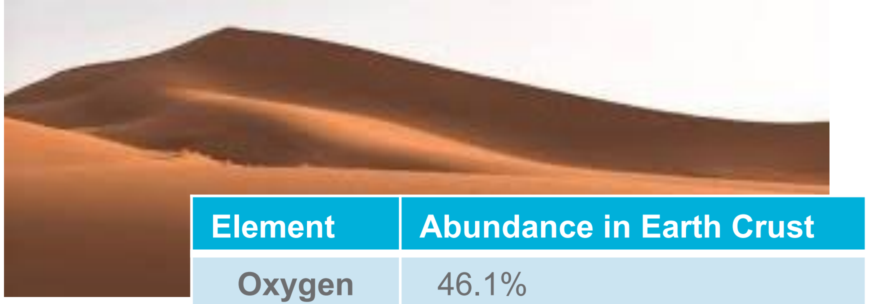


Motivation – monolithic III-V on Si for photonics

Silicon

- Cheap, abundant, self-passivating
- Material of choice for electronics
- >60 years of semiconductor technology
- Low-loss high density silicon passive photonics

→ Silicon photonics as platform

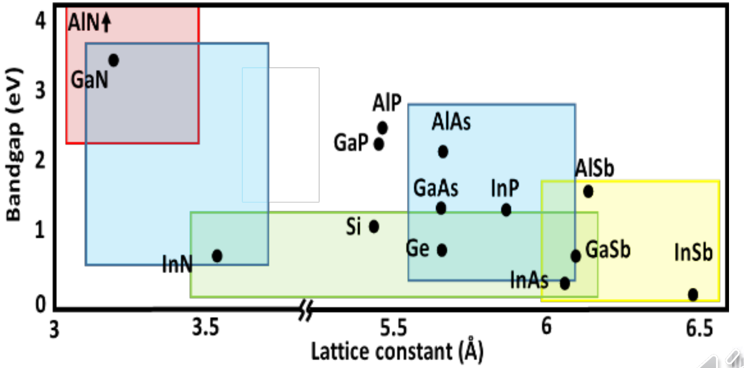


Element	Abundance in Earth Crust
Oxygen	46.1%
Silicon	28.2%
Indium	0.000016%

Need III-Vs for light-emission

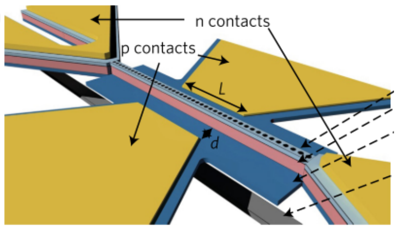
- Direct band gap → pre-requisite for lasing
- Heterostructures → efficient opto-electronic devices
- Tunable bandgap → broad spectral range
- More efficient, low-noise photodetectors

→ Template-Assisted Selective Epitaxy for local integration of III-V on silicon



III-V epitaxy on Si for photonics

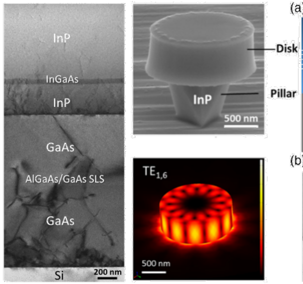
Wafer bonding



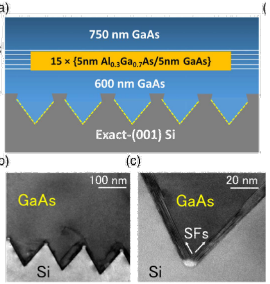
G. Crosnier, Nat. Phot. (2017)

- High material quality
- Dense integration challenges

Planar epitaxy



B. Shi, APL (2017)

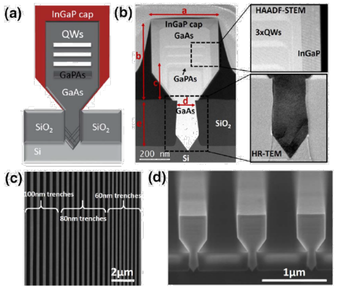


Y. Wan, Optica (2017)

- Monolithic on Si
- Issues with material defects
- Topography

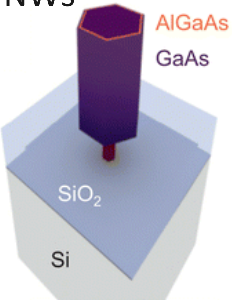
Selective epitaxy

Aspect-Ratio Trapping



Y. Shi, Optica (2011)

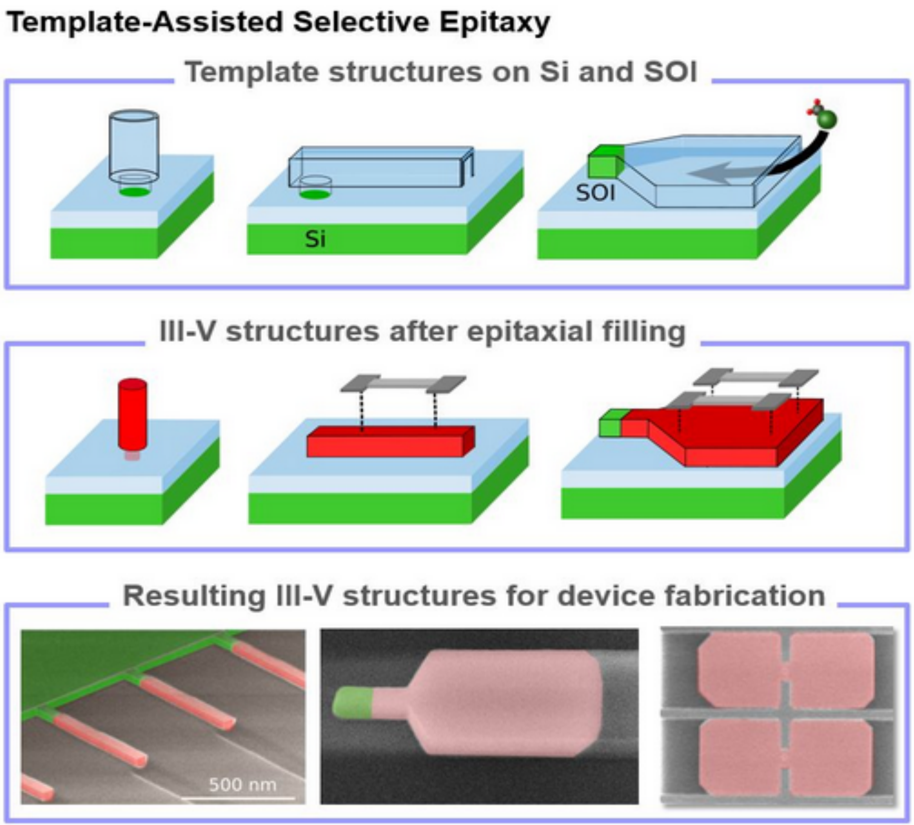
NWs



B. Mayer, Nano Lett. (2015)

- Scalable
- No thick buffers
- Geometry may be limiting

Template-Assisted Selective Epitaxy (TASE)



Concept

1. Start epitaxy from a single nucleation point
2. Keep area of epitaxial interface small
3. Expand seed and guide growth within oxide template

Benefits:

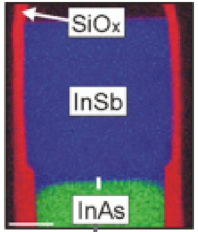
- Avoids lateral overgrowth of junctions associated with NW growth
- Easy-alignment to other Si features
- Can repeat process to get multiple III-Vs on the same wafer.

🕮 P. D. Kanungo et al. Nanotechnology (2013)
🕮 M. Borg et al. Nano Letters (2014)
🕮 H. Schmid et al. APL (2015)
🕮 L. Czornomaz et al. VLSI (2015)

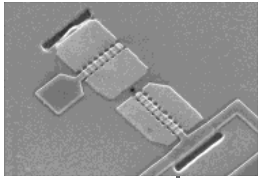
Timeline of work on TASE

Epi- Growth

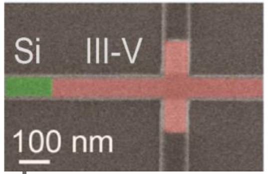
InSb/ InAs first trials



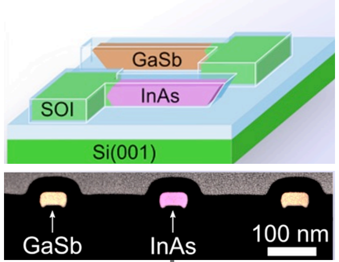
CELO growth



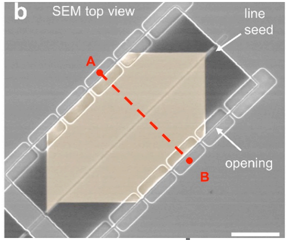
Arbitrary shapes



Co-integration (InAs/GaSb)

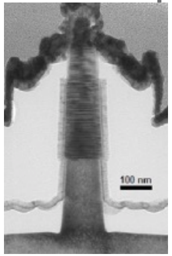


Crystal phase control (InP)

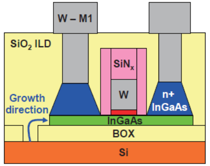


Time 2013 2014 2015 2016 2017 2018 2019 2020

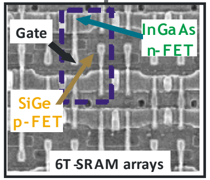
Applications



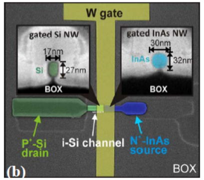
P-TFET InAs-Si



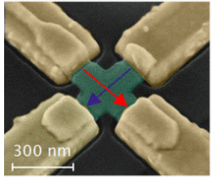
MOSFET InGaAs & InAs



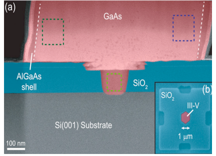
Hybrid SRAM



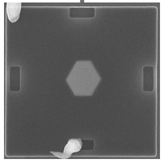
C-TFET



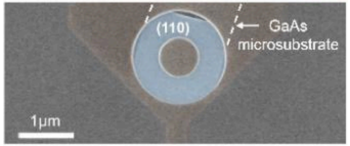
Ballistic NW transport



GaAs microdisk laser



InP microdisk laser

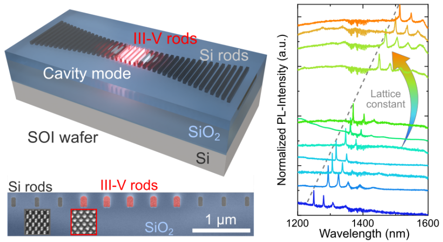


GaAs virtual substrate laser

K. E. Moselund, NUSOD 2020. kmo@zurich.ibm.com

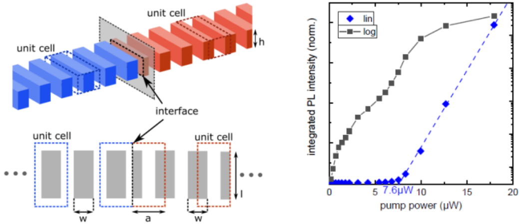
Overview of current photonic activities in our group

Hybrid III-V/Si photonic crystals (PhCs)



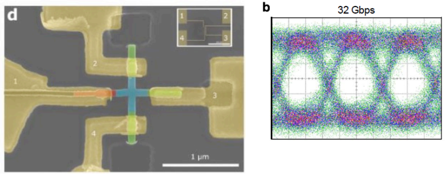
📖 S. Maute et al. Arxiv 2020

Topological PhCs



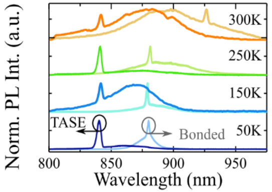
📖 M. Scherrer, submitted IEDM 2020

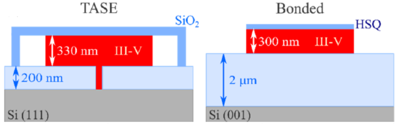
First monolithic integrated InGaAs detectors on Si



📖 S. Mauthe et al. Nature Com. 2020

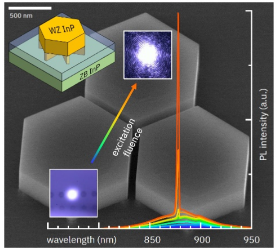
Microdisk lasers by TASE and bonding





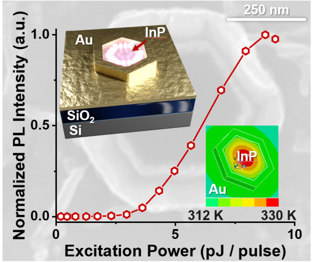
📖 S. Mauthe et al. J.S.Top. Quant. Electron. 2019

InP wurtzite laser



📖 P. Staudinger et al. arXiv:2004.10677, 2020

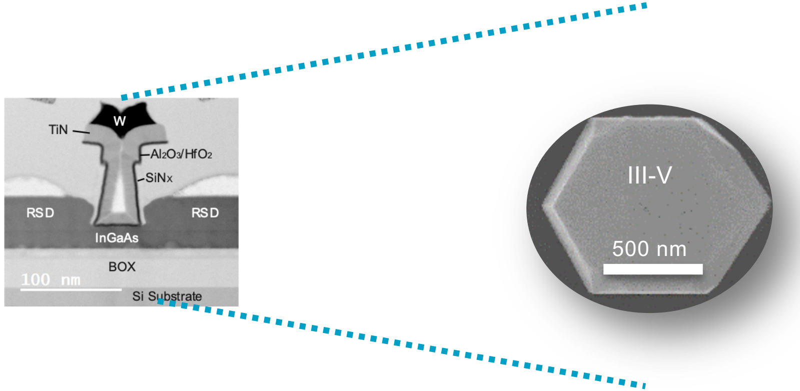
Metal-clad InP bonded nanodisk lasers



📖 P. Tiwari et al. arXiv:2009.03572, 2020

III-V TASE Microdisk lasers

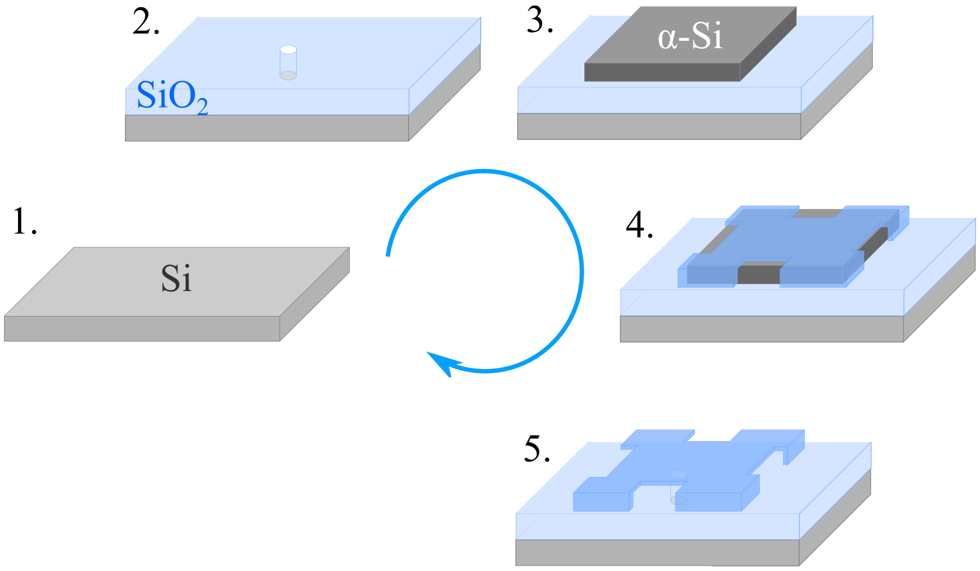
Monolithic optoelectronic devices



Challenges

- Much larger device volume compared to electronics→ control of composition and defects is critical
- Dielectric isolation from substrate → thicker BOX = more topography
- Roughness from template → challenging for quantum well integration

Novel Technique to integrate high-quality III-V on Si

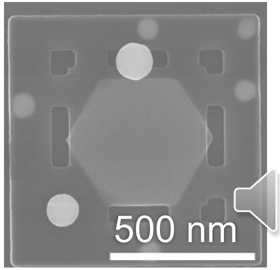


Template-assisted selective epitaxy (TASE)

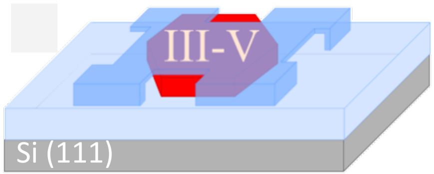
1. Si wafer
2. Deposition and patterning of SiO_2
3. Deposition and patterning of sacrificial α-Si layer
4. Deposition of oxide shell and local opening to expose α-Si
5. Etch of the sacrificial α-Si layer
6. MOCVD growth of III-V material

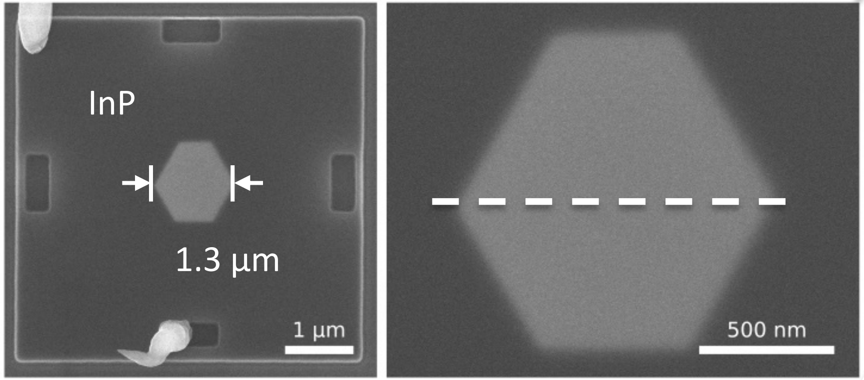
→ Growth expands in lateral direction

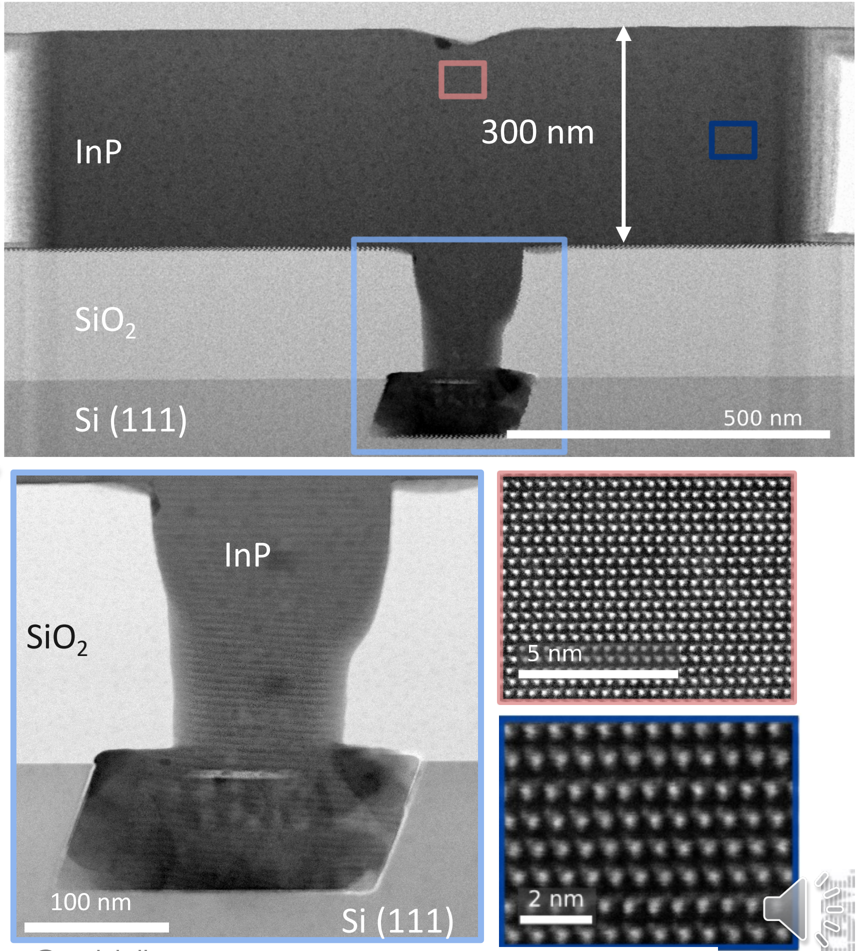
→ Growth duration defines expansion



InP microdisks on Si(111)







→ Single crystalline InP microdisk structures

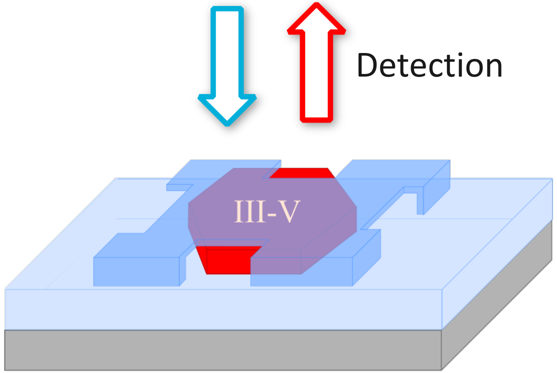
→ No etching required, Atomically flat side walls

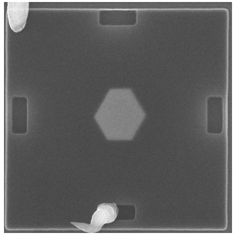
→ No propagating defects

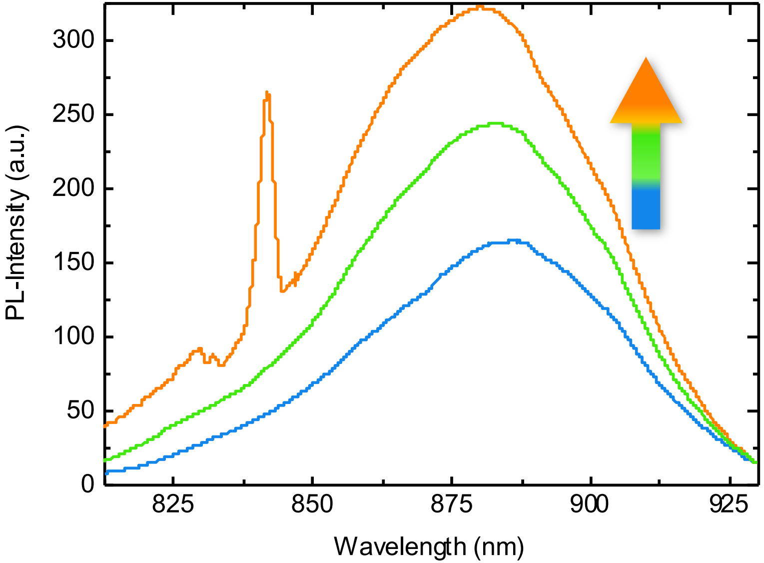
📖 S. Mauthe, JSTQE, 2019

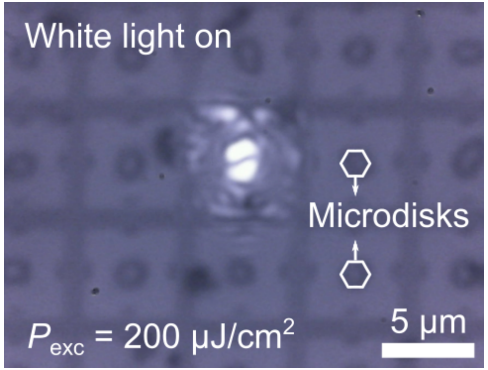
InP microdisk laser with RT performance

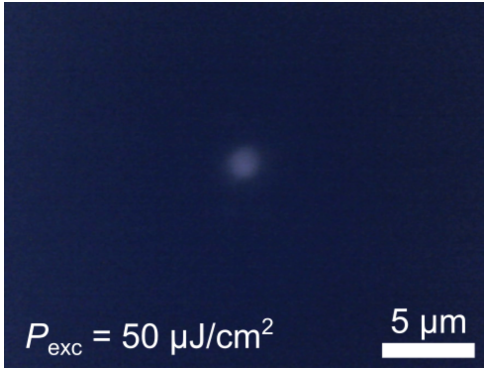
750 nm ps-pulsed
excitation





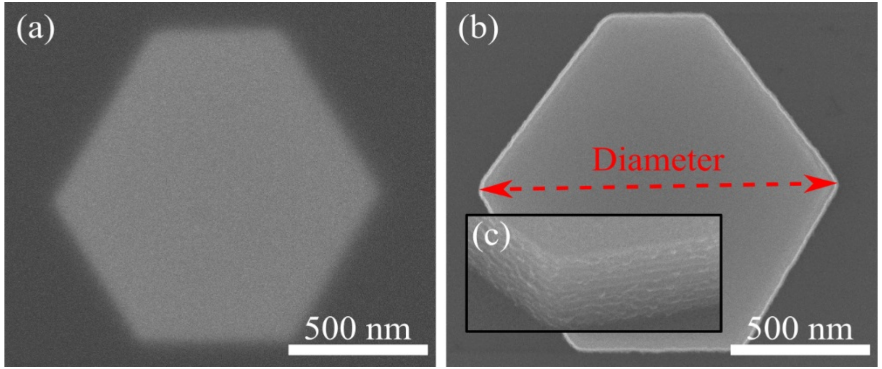




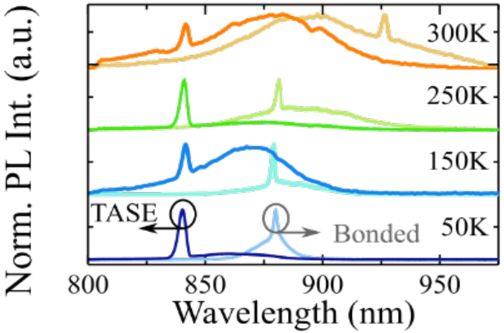


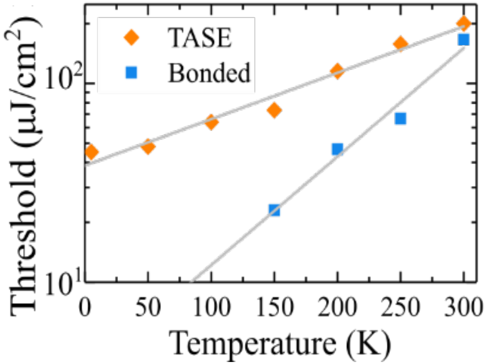
S. Mauthe, JSTQE, 2019

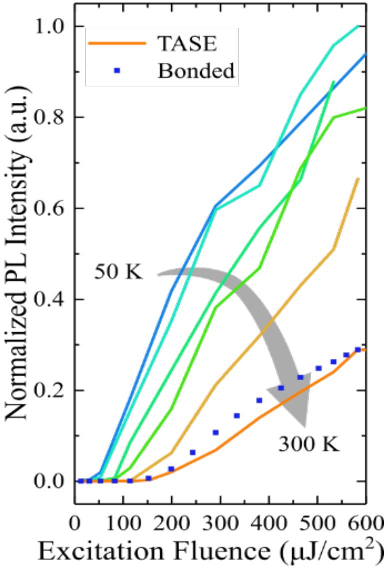
Comparison InP microdisks – bonded vs. TASE



- Wafer bonding InP on Si and InP dry etching
- PL of TASE slightly shifted
  - Possible WZ/ZB mixing
- TASE show weaker T-dependence
  - Performance limited by bulk twin defects
  - Bonded structures limited by surface defects

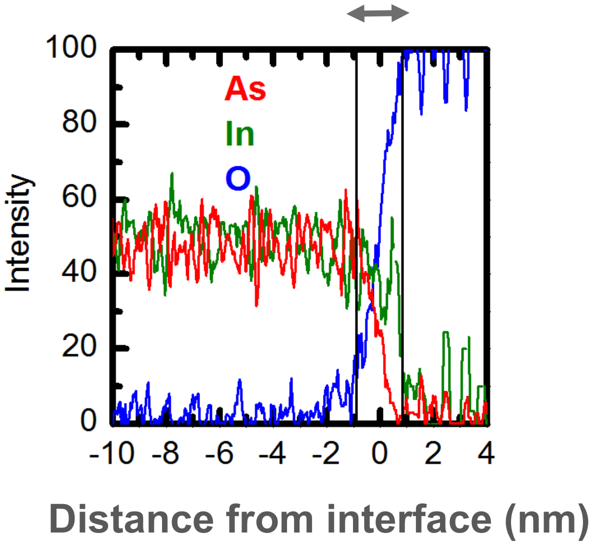




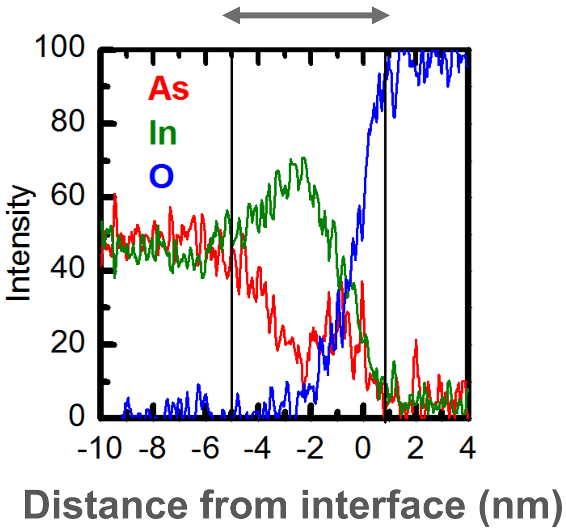


📖 S. Mauthe, IEEE J. Sel. T. Quant. Electron. (2019)

III/V - template interface



InAs in template

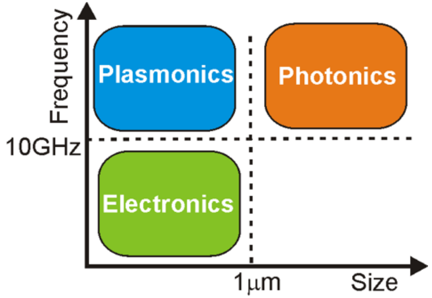


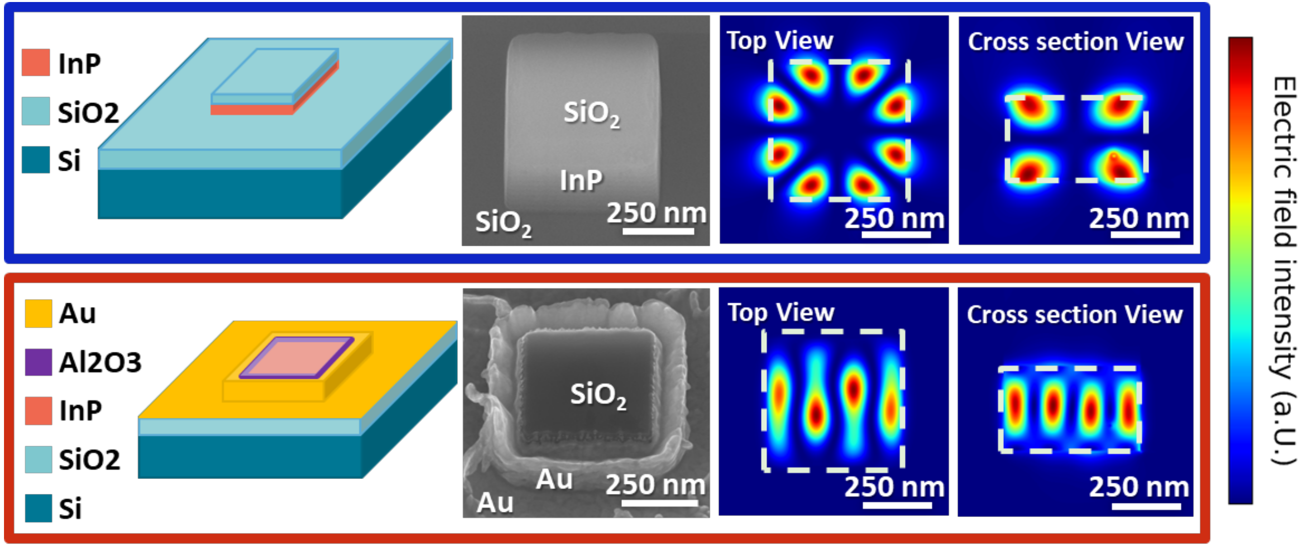
InAs w/o template

Reduced interface oxidation
→ Improved transport properties

Example 1:
Metal-clad cavities

Plasmonics – path for downscaling

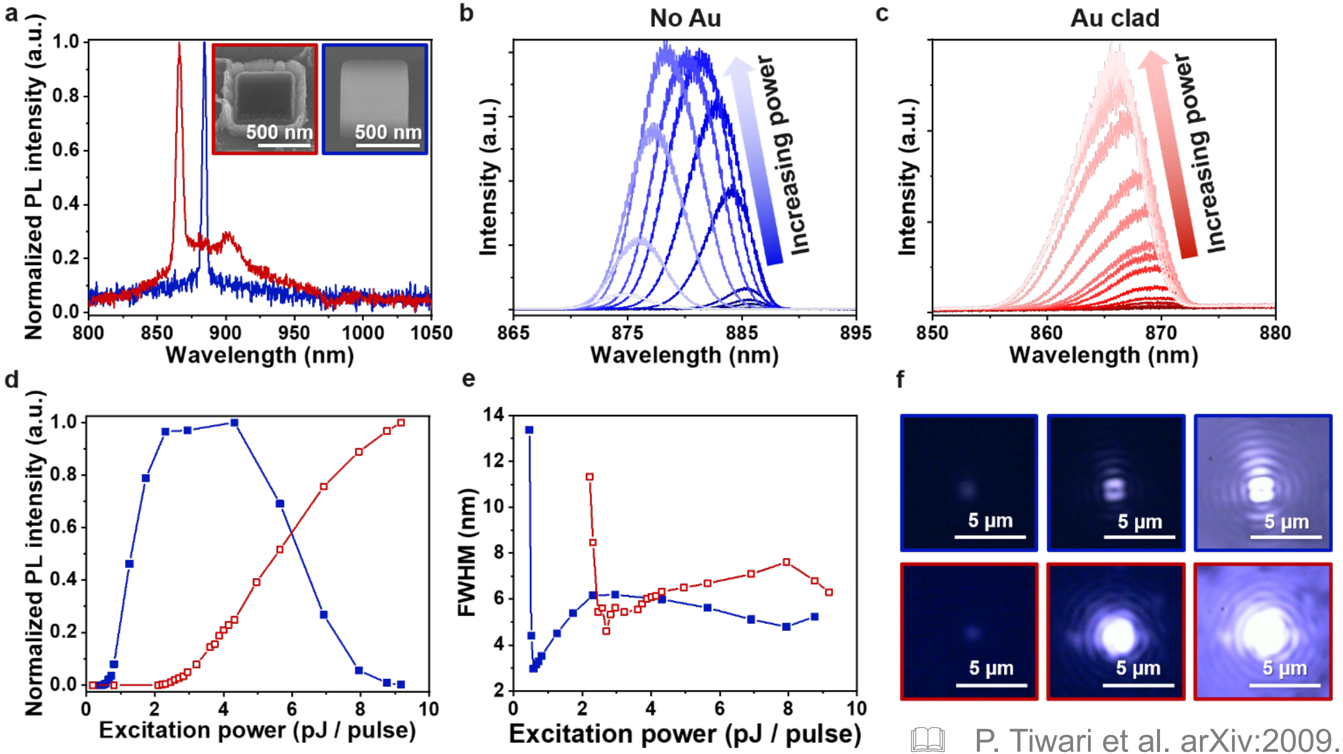




🕮P. Tiwari et al. IEEE IPC, 2020. 🕮 P. Tiwari et al. arXiv:2009.03572, 2020

- Hybrid plasmonic-photonic modes may allow scaling beyond diffraction limit
- Different mode-patterns in photonic vs. metal-clad cavities
- Differentiation of the impact of the metal – plasmonics, reflectivity, heat removal

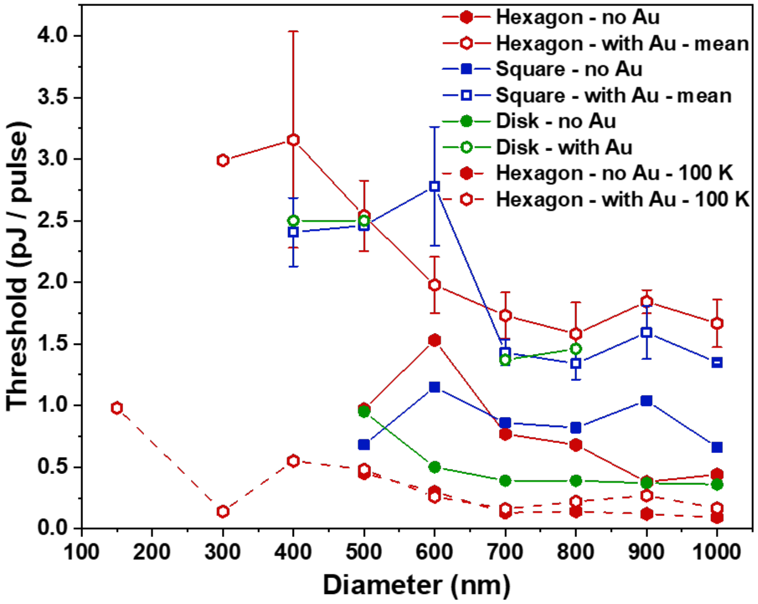
Metal-clad cavities – comparison of performance



📖 P. Tiwari et al. arXiv:2009.03572, 2020

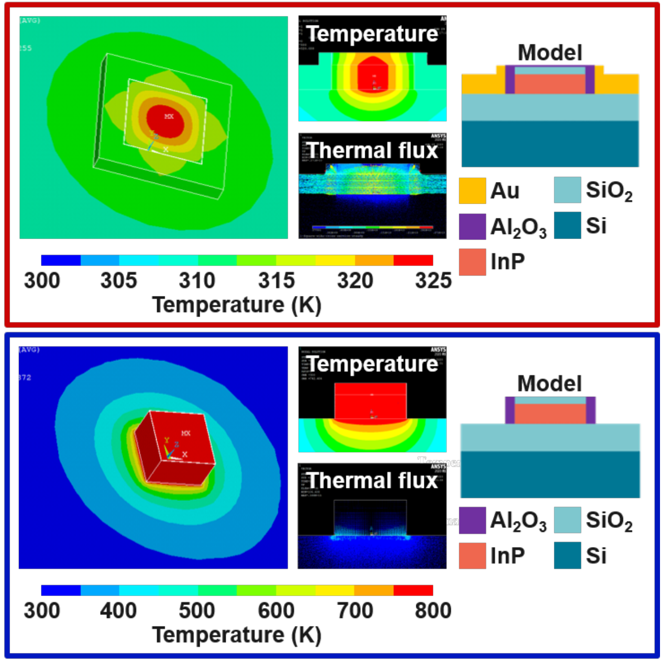
- Same cavities (different shapes) – measured with and without a metal cavity
- Significant differences in performance

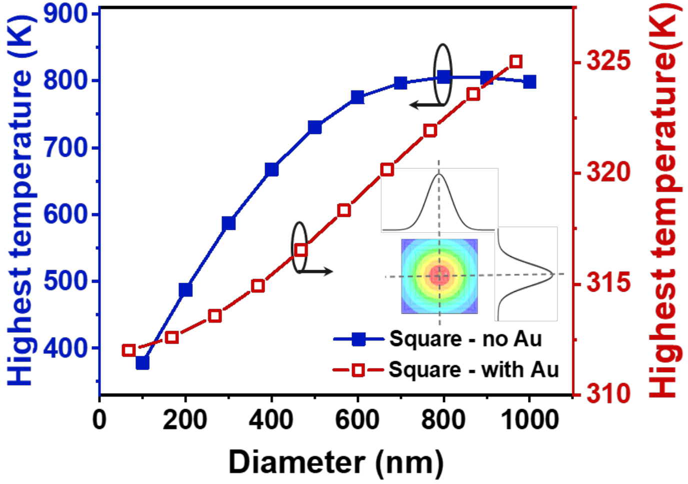
Scaling behavior



- Minor effect of the shape (volume).
- Metal-clad cavities
  - Higher thresholds
  - Reduced drop-off with pump power
  - Lase at smaller dimensions
- At 100K, thresholds overlap, and the metal-clad can be even further scaled.

Thermal simulations





P. Wen, Ansys Thermal Simulations

- Understanding the heat dissipation path is crucial for optimization
- Au acts as a heat sink and dramatically reduces maximum temperature (~400K)

Role of simulations in Metal-clad lasers

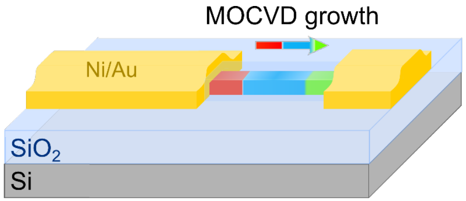
- Lumerical: Different mode patterns in photonic and metal-clad cavities, but no stand-alone clarity about role of metal
- Ansys: Thermal simulations are a crucial part of understanding behaviour in these devices.

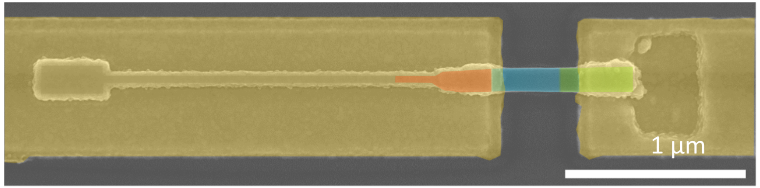
Still on the wishlist:

- Presently only the absorption lossin the metal is accounted for, how about scattering in the metal and at rough interfaces?
- Coupling between Ansys and Lumerical/Sentaurus – contributions of the lasing mode itself.

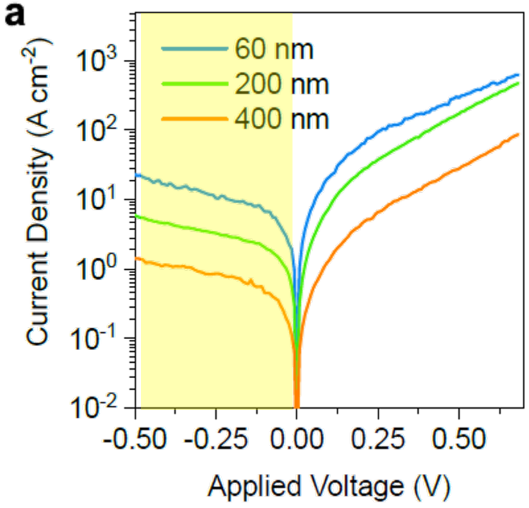
Example 2:
Monolithic III-V detectors

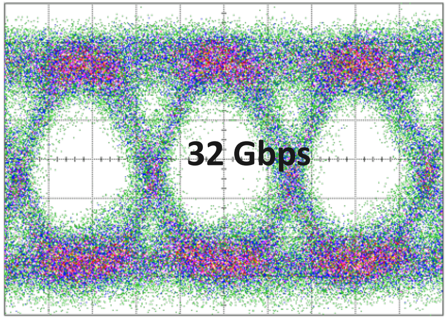
Ultra-scaled InGaAs *p-i-n* Photodetector





Light detection





📖 S. Mauthe, OFC 2020

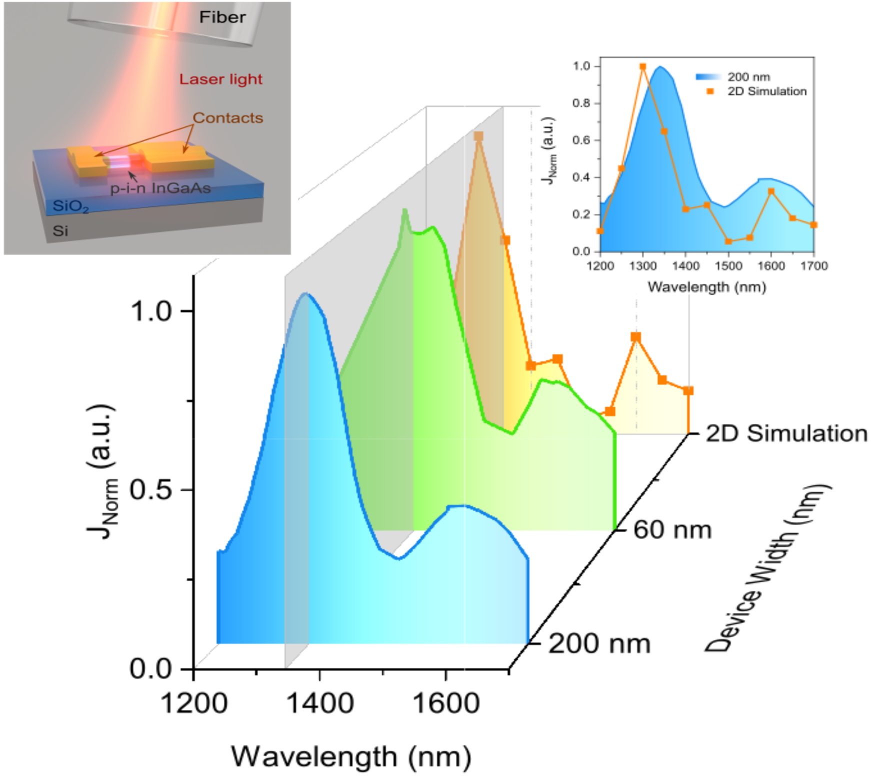
- **Devices are scaled:**
  - 60 nm high
  - 60-500 nm wide
  - 1 µm long

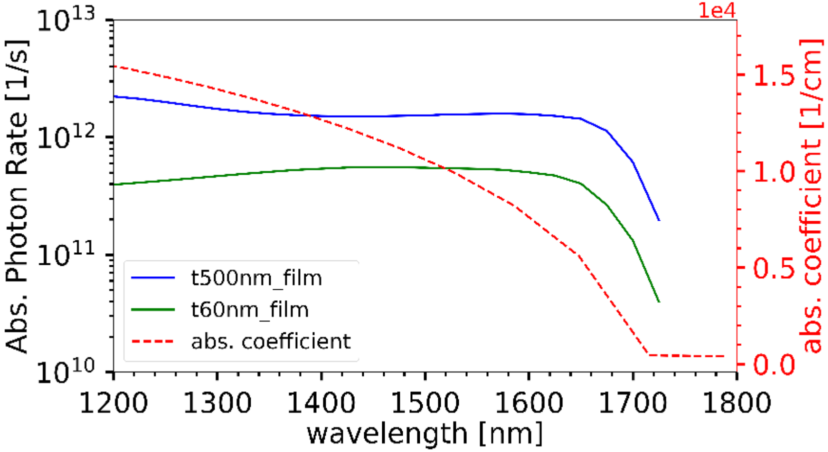
→ Small footprint devices enabled by in-plane growth

→ Low dark current (nA) required for efficient detection

→ Demonstrated operation > 25 GHz

Non-linear spectral dependence

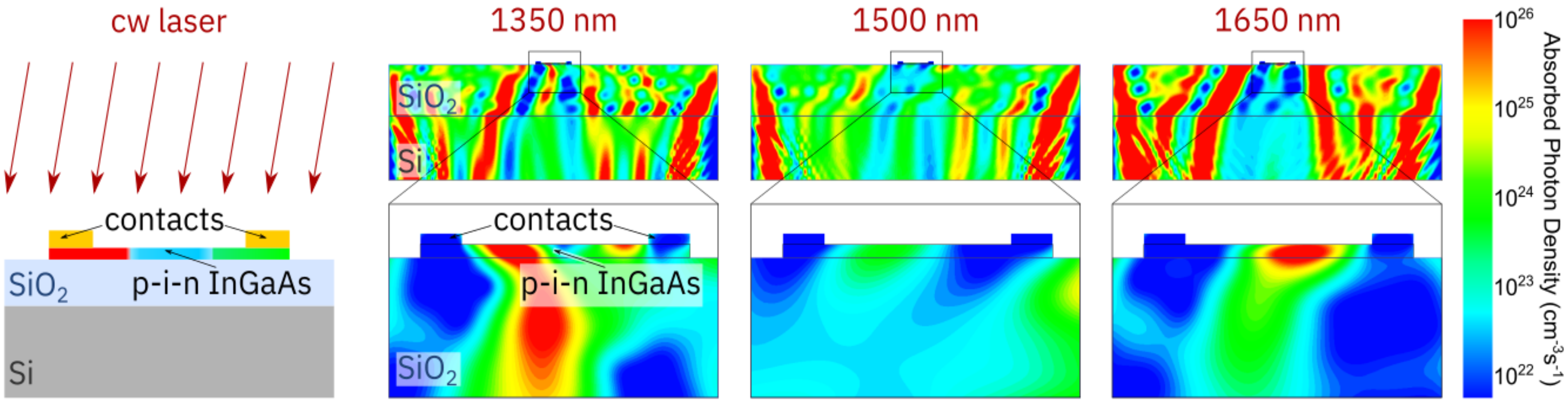




- Free-space illumination with supercontinuum source → two peaks in the absorption spectra.
- Not expected purely from the material response

📖 S. Mauthe, Nature Com. (2020)

Insights from TCAD simulation



- TCAD simulations using Sentaurus Synopsys
- The thin film thickness (60 nm) results in reflections
- The exact contact lay-out is important as it results in local wavelength dependent enhancement of the field.

In-depth insights in #D06, titled as "Scaling Effects on the Plasmonic Enhancement of Butt-Coupled Waveguide Photodetectors“, by Qian Ding.

Summary

Summary

- Introduced the TASE epitaxial growth technique as a platform for the local monolithic integration of III-V for photonics
- Introduced our work on mircodisk lasers as a means for understanding the importance of defects
- Demonstrated two different case studies where simulations provide essential guidance on device design
  - Metal-clad nanolasers
  - Scaled monolithic detectors

From a simulation perspective – important questions

- Coupling of photonic and electronic simulations may be challenging
  - Fully coupled 3D opto-thermal-electrical simulations (including self-heating self-consistently)
- Not all defects are alike
  - The location of the defects and your operating conditions matter
- How can we as experimentalist provide the right data to enable accurate calibration of simulations.
- Alignment of objectives

Co-authors & acknowledgements

Nanophotonics

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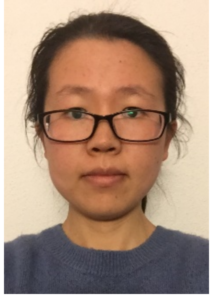
TCAD Simulations (ETHZ)

Andreas Schenk

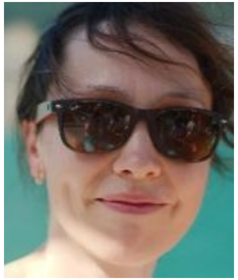
Qian Ding



III-V growth development & Materials

Heinz Schmid

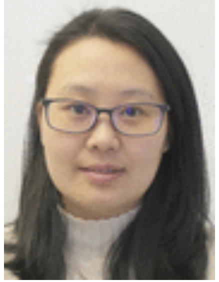
Marilyne Souza



Philipp Staudinger

Thermal Simulations

Pengyan Wen



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Thank you for your attention

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Questions

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